A Genetic Algorithm Based Security Constrained Economic Dispatch Approach for LMP Calculation

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Abstract

In restructured electricity markets, an effective transmission pricing method is required to address transmission issues and to generate correct economic signals. Transmission line constraints can result in variations in energy prices throughout the network. These prices depend on generator bids, load levels and transmission network limitations. Locational Marginal Pricing (LMP) is a dominant approach in energy market operation and planning to identify nodal prices and manage transmission congestion. This paper presents a Genetic Algorithm (GA) based security constrained economic dispatch (SCED) approach to evaluate LMP's at all buses while minimizing total system fuel cost for a constrained transmission system, with and without considering system losses. The proposed GA based SCED approach is applied to EEE 14 bus, 75 bus Indian power system and New England 39 bus system. The results obtained are compared with conventional Linear Programming based DCOPF using Power World Simulator. Both fixed and linear bids are considered for generators. The load is assumed to be inelastic. The proposed GA based SCED for LMP calculation is proved to be very simple, reliable and efficient in all the studied cases. Further, the optimal redispatch of generators using GA leads to overall reduction in generation fuel cost.

Keywords

Delivery Factors; Fixed Bid; Genetic Algoirthm; Generation Shift Factors; Linear Bid; LMP

Nomenclature

k – line no

i – bus no

B – reactance matrix

a – sending end bus of line k

b – receiving end bus of line k

a_i, b_i, c_i – coefficients of fuel cost function

S_j – a feasible solution

Introduction

Under deregulated electricity market environment, transmission network plays a vital role in supporting the transaction between producers and consumers. Transmission congestion occurs when transmission lines or transformers operated at or above their thermal limits preventing the system operators from dispatching additional power from a specific generator. Presently there are two pricing structures [8] that are being used in a competitive energy market to account for congestion: the uniform pricing method (MCP) and the nonuniform pricing method (LMP). LMP is defined as the marginal cost of supplying the next increment of electric energy at a specific bus while considering the generation marginal cost and the physical aspects of the transmission system. Buyers pay ISO based on their LMP for dispatched energy. The ISO pays sellers based on their respective LMP's. This method is under practice at many ISO's such as PJM, New York ISO, ISO-New England, California ISO, Midwest ISO, ERCOT etc [4], [15] and [18]. The LMP difference between two adjacent buses is the congestion cost which arises when the energy is transferred from one location (injection) to the other location (withdrawal). Transmission losses also cause differences in LMP's. Marginal losses represent incremental changes in system losses due to incremental demand changes. Incremental losses yield additional costs which are referred to as the cost of marginal losses [23]. Thus LMP is the summation of the costs of marginal energy, marginal loss, and congestion. Therefore LMP is stated as follows:

$$\text{LMP}=\text{generation cost}+\text{congestion cost}+\text{loss cost} \qquad (1)$$

LMP's are calculated as the result of optimal power flow (OPF) or security constrained economic dispatch (SCED) either in day ahead market (DAM) or real-time market (RTM). Several papers have reported different models for LMP calculation. Reference [23] presented different methods and properties on LMP calculations based on DCOPF with and without loss. Reference [1] gives a systematic description on how the LMP's are produced; it also described both the modelling and implementation challenges and solutions. Reference [24] described ACOPF based LMP calculation considering distributed loss. Reference [3] demonstrated an iterative DCOPF based algorithm with lossless model, considering marginal losses, and with fictitious nodal demand model to calculate LMP. All these 3 models are solved with linear programming. Reference [20] presented Nodal pricing with Genetic Algorithm for congestion management with DCOPF for lossless system.

The present paper proposed a GA based SCED approach with linear incremental cost curve which gives true marginal cost of generation. Both the models with and without losses have been attempted for fixed generation bids and linear generation bids. Section 2 describes different types of bids used for generators. The problem formulation for LMP calculation using delivery factors with and without considering losses is discussed in section 3. Section 4 presented implementation of GA. Section 5 gives results and discussions for IEEE 14 bus system [17], 75 bus Indian power system [25] and New England 39 bus test system [26]. Section 6 concludes the paper.

Types of Generator Bids

In general, generators bids depend on many factors, some of which (e.g. strategic behaviour) are difficult to model. To avoid excessive complexity, generators bids are assumed to be equal to their incremental costs for perfect competition. Two bidding models are generally used, namely: fixed generator bids (corresponding to piecewise-linear heat rates) and linear bids (corresponding to quadratic heat rates).

Fixed Bids

The heat rate curve is converted to an approximate fixed incremental heat rate for each unit through Linear regression method. The cost changes in steps with respect to generation. The fixed bid curve for piecewise linear cost characteristics is shown in Fig. 1.

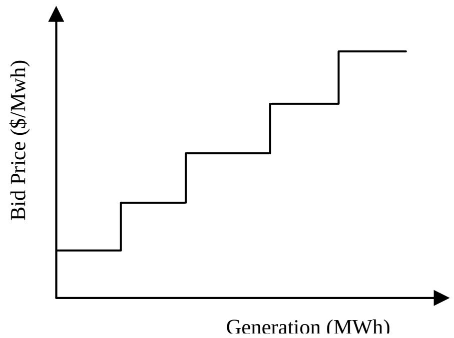

FIG. 1 FIXED BID

Linear Bids

The non-smooth nature of the fixed bid in Fig.1 may result in step changes in prices at certain load levels. One way to mitigate this is to use linear bids for the generating units. This will result in a much smoother supply curve as shown in Fig.2.

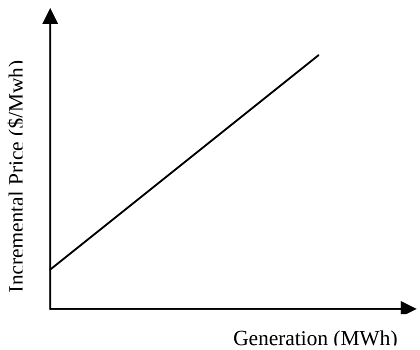

FIG. 2 LINEAR BID

The generator cost curve is given by (2)

$$C_{G_i}(P_{G_i}) = a_i + b_i P_{G_i} + c_i P_{G_i}^2 \quad (\$) \tag{2}$$

where $C_{G_i}(P_{G_i})$ is the cost of unit '*i*' of generating P_{G_i} MWh, a_i is the no-load cost, b_i is the linear cost coefficient and c_i is the quadratic cost coefficient of unit i. The incremental costs of the units can be modelled as fixed quantities (resulting in fixed bids Fig.1); or can be expressed as linear function of the unit outputs (resulting in linear bids Fig.2) as in (3).

$$\frac{dC_{G_i}(P_{G_i})}{dP_{G_i}} = b_i + 2c_i P_{G_i} \quad (\$/\text{Mwh}) \tag{3}$$

Mathematical formation for LMP Calculation

In literature LMP calculation with DCOPF with and without considering line losses for fixed bids is solved with Linear Programming approach [3]. In the present paper active power generations of the generators except slack generation are considered in chromosome using GA. The obtained PG's are used in calculation of

LMP with and without loss for the congested transmission system. Generation Shift factors (GSF) have been used for the calculation of transmission line flows. Delivery factors (DF) at buses have been used to include the impact of marginal losses on LMP.

Generation Shift Factor

Generation shift factor is the ratio of change in power flow of line 'k' to change in injection of power at bus 'i'. GSF coefficient can be computed as

$$GSF_{k-i} = \frac{(B^{-1}_{(a,i)} - B^{-1}_{(b,i)})}{X_k} \quad (4)$$

where

B^{-1} = inverse of B (the imaginary part of Y bus matrix)

X_k = reactance of line k

a is sending bus and b is receiving bus of line k

Delivery factor

The delivery factor (DF) at the ith bus represents the effective MW delivered to the customers to serve the load at that bus.

It is defined as

$$DF_i = 1 - LF_i = 1 - \frac{\partial P_{loss}}{\partial P_i} \quad (5)$$

where LF_i = loss factor at bus i

$$P_{loss} = \sum_{k=1}^{M} F_k^2 \times R_k \quad (6)$$

$$F_k = \sum_{i=1}^{N} GSF_{k-i} \times P_i \quad (7)$$

where F_k = line flow of line k ,

R_k = resistance of line k,

$P_i = P_{G_i} - P_{D_i}$ = injection at bus i

GSF_{k-i} = generation shift factor to line 'k' from bus 'i'.

The loss factor (LF) at the i^{th} bus may be viewed as the change of total system loss with respect to a 1 MW increase in injection at that bus.

LMP Calculation without Losses Using GA Based SCED

In this method the objective function is minimization of total production cost subjected to demand balance and line flow constraints. This problem is solved with GA and the total fuel cost is compared with LP approach.

Therefore the objective function is

$$\text{Minimize} \quad J = \sum_{i=1}^{N} MC_i * P_{G_i} \quad (8)$$

$$\text{s.t.} \quad \sum_{i=1}^{N} P_{G_i} = \sum_{i=1}^{N} P_{D_i} \quad (9)$$

$$F_k \le \text{limit}_k \quad (10)$$

for k=1,2,……M

$$P_{G_i}^{\min} < P_{G_i} < P_{G_i}^{\max} \quad (11)$$

for i=1,2,……N

where

N = number of buses

M = number of lines

$MC_i = b_i + 2c_i P_{G_i}$ (\$/Mwh), marginal cost at Bus i

P_{G_i} = output power of generator at bus i (Mwh)

P_{D_i} = demand at bus i

limit_k = thermal limit of line k.

LMP Calculation with Losses Using GA Based SCED

In LMP based electricity markets, system losses have significant impact on the economics of power system operation. So system losses have to be taken into account for obtaining more accurate LMP's. In this model it is assumed that total system loss is supplied by slack bus generator.

The algorithm for this problem is same as that in section C except (9). Here (9) is modelled as

$$\sum_{i=1}^{N} DF_i \times (P_i) + P_{loss} = 0 \quad (12)$$

where DF_i = delivery factor at bus i

P_{loss} = total system loss of the system

P_{loss} in (12) is used to offset the doubled average system loss caused by the marginal loss factor (LF) and the marginal delivery factor (DF).

After getting power outputs of generators for the above dispatch, slack bus power is calculated using (9) or (12) and the price at the reference (slack) bus has to be calculated by substituting slack bus power either in fixed bids or linear bids. At the reference bus both loss

price and congestion price are always zero. Therefore, the price at the reference bus is equal to the energy component.

Now the LMP formulation at a bus B can be written as

$$LMP_B = LMP^{energy} + LMP_B^{cong} + LMP_B^{loss} \quad (13)$$

$$LMP^{energy} = \lambda = \text{price at the reference bus} \quad (14)$$

$$LMP_B^{cong} = -\sum_{k=1}^{M} GSF_{k-B} \times \mu_k \quad (15)$$

where μ_k is the constraint cost of line k, defined as:

$$\mu_k = \frac{\text{change in total cost}}{\text{change in constraint's flow}}$$

$$LMP_B^{loss} = \lambda \times (DF_B - 1) \quad (16)$$

($LMP_B^{loss} = 0$ for lossless power system)

Implementation of Genetic Algorithm Approach for LMP Calculation

There are several methods available to solve an optimization problem, some of which are simulated annealing algorithm, differential evolution algorithm, ant colony method, music based harmony search method, particle swarm optimization, artificial bee colony algorithm and genetic algorithm. All these methods are population based search methods. Genetic algorithm is the simplest method among all the above optimization techniques, which is the main reason for selecting GA to solve the problem for calculation of LMP. Genetic algorithms are implemented as a computer simulation in which a population of abstract representations (called chromosomes) of candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem evolves toward better solutions. GAs start with random generation of initial population and then the selection, crossover and mutation are performed until the best population is found. The present work employed roulette wheel parent selection technique, Single point Crossover and bit wise mutation.

In this method power generations of generators (P_{G_i}) except slack bus are taken as the control variables in the chromosomes. The problem is formulated as minimizing the objective function (8) subjected to (9) or (12) as equality and (10) as inequality constraints.

Constraints Handling

Constraints are handled by using penalty function approach. If an individual S_j is a feasible solution and satisfies all constraints, its fitness will be measured by taking the reciprocal of the fuel cost function else need to be penalized. Using the exterior penalty function approach, the violated operating constraints are incorporated as penalties in objective function.

Calculate the GA fitness function, FF = 100/ (1+ J+ penalties). The penalties are calculated for (10), (12) and slack bus power if they are violated as follows:

Penalty function for line flows:

pcost_f= lambda_f(k)*df*(|pflow(k)|-limit)^2

Penalty function for power balance:

pcost_error= lambda_error*(error)^2

Penalty function for slack bus power:

pcost_s=lambda_s*ds* (pgen (nslack)-s_limit)^2

where lambda_f(k), df, lambda_error, lambda_s, ds are all constants and taken same values for all cases in each bus system.

Algorithm for LMP Calculation Using GA Based SCED Approach

Step 1: Read no. of buses, no. of lines, slack bus number, and Bus data. Read GA parameters like population size, chromosome length, no. of units, maximum no. of generations, elitism probability, crossover probability, mutation probability, and epsilon. Read a_i, b_i, c_i coefficients; min. and max. limits of generators. Read line data including line thermal limits.

Step 2: Generate randomly power generations of all generators except slack generator and decode them.

Step 3: Calculate Generation shift factors using (4)

Step 4: Calculate line flows using (7)

Step 5: Calculate the system loss i.e., P_{loss} using (6) for LMP with loss case.

Step 6: Calculate delivery factors at each bus using (5)

Step 7: Calculate P_{gen} of slack bus using (9) for without loss case and (12) for with loss case.

Step 8: Check for line flow limits using (10). If the line limits are violated add penalties to objective function.

Step 9: Check for slack bus power limits using (11). If the slack bus power limits are violated adding penalty to objective function.

Step 10: Calculate the marginal fuel costs of all units with the randomly generated PG's; calculate the total cost (8) and then calculate the fitness function = 100/ (1+ total cost+ penalties).

Step 11: Sort the chromosomes in the descending order of fitness.

Step 12: Is generation = max. no. of generations. If yes stop else go to step 12.

Step 13: If fitness (1) == fitness (psize)→problem converged

Calculate the energy price of the reference bus either with fixed bids or with linear bids and then calculate LMP's at all buses (13). STOP.

Step 14: Use selection, crossover and mutation operators. Generate new population.

Generation = Generation +1; Go to step 4.

Case Studies

The developed GA based SCED approach for LMP calculation is applied to IEEE 14bus system [17], 75 bus Indian power system [25] and New England 39 bus system [26]. GA parameters used are Population size: 40, Number of bits for each generator in the chromosome: 12, Elitism probability: 0.15, Crossover probability: 0.85, Mutation probability: 0.01, Tolerance: 0.0001. IEEE 14 bus system has 2 generators, 75 bus system has 15 generators and 39 bus system has 10 generators. The proposed GA based approach is compared with LP based DCOPF using Power world simulator. In LP approach for with loss case, loss is calculated from base case data using ac (alternating current) load flow and is added to the slack bus as load.

IEEE 14 Bus Test System

Table 1 presents the active power generations of generators for the IEEE 14 bus system without losses. Table 2 presents the active power generations of generators for the IEEE 14 bus system considering system transmission losses. For the base case loading, 9th line connecting 4-9 buses is congested with both LP approach and GA approach for both with and without loss cases with base case loading only. The corresponding LMPs at all buses are presented in Tables 3 and 4. The generation redispatch with GA approach leads to considerable savings in the fuel costs compared to LP approach. Considering linear bids for the generators results in further savings in fuel costs. From the LMP values it can be observed that loads away from generators have more locational marginal prices, because of the addition of congestion costs and loss costs. Fig. 3 presents a comparison of optimal fuel costs for all the studied cases. It is obvious that the cost is minimum using GA with linear bids. The graphs in Fig. 4 and Fig. 5 show the variation in LMP's in the cases without and with loss for all attempted methods.

TABLE 1 ACTIVE POWER GENERATIONS OF GENERATORS WITHOUT LOSSES

Generator bus No.	Power Generations in MW without loss		
	LP approach Fixed bids	GA approach	
		Fixed bids	Linear bids
1 (slack bus)	142	141.37	141.37
2	117	117.62	117.62
Fuel cost ($/hr)	3222.97	3223.11	2985.01

TABLE 2 ACTIVE POWER GENERATIONS OF GENERATORS WITH LOSSES

Generator bus No.	Power Generations in MW with loss		
	LP approach Fixed bids	GA approach	
		Fixed bids	Linear bids
1 (slack bus)	147.143	144.9	144.9
2	117	117.62	117.62
Loss (MW)	5.143	3.527	3.527
Fuel cost ($/hr)	3286.434	3266.64	3063.56

TABLE 3 LMP'S AT ALL BUSES WITHOUT LOSSES

Bus No.	LMP's at all buses ($/MWh)		
	LP approach Fixed bids	GA approach	
		Fixed bids	Linear bids
1	12.34	12.34	22.00
2	12.19	12.18	21.85
3	11.76	11.75	21.42
4	11.38	11.38	21.05
5	12.91	12.91	22.58
6	23.77	23.76	33.43
7	27.58	27.57	37.24
8	27.58	27.57	37.24
9	36.10	36.09	45.76
10	33.91	33.9	43.57
11	28.93	28.92	38.59
12	24.74	24.74	34.4
13	25.50	25.5	35.17
14	31.47	31.46	41.13

TABLE 4 LMP'S AT ALL BUSES WITH LOSSES

Bus No.	LMP's at all buses ($/MWh)		
	LP approach Fixed bids	GA approach	
		Fixed bids	Linear bids
1	12.34	12.34	22.52
2	12.16	12.27	22.56
3	11.64	12.11	22.69
4	11.20	11.58	22.08
5	13.02	13.34	23.8
6	25.95	26.28	36.74
7	30.49	30.86	41.36
8	30.49	30.86	41.36
9	40.63	41.00	51.50
10	38.02	38.40	48.91
11	32.09	32.45	42.95
12	27.11	27.48	37.99
13	28.02	28.40	38.91
14	35.12	35.55	46.09

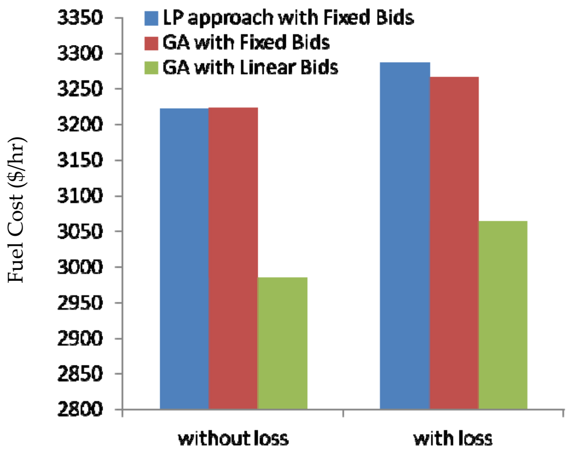

FIG. 3 FUEL COST COMPARISON GRAPH FOR WITHOUT AND WITH LOSSES OF IEEE 14 BUS SYSTEM

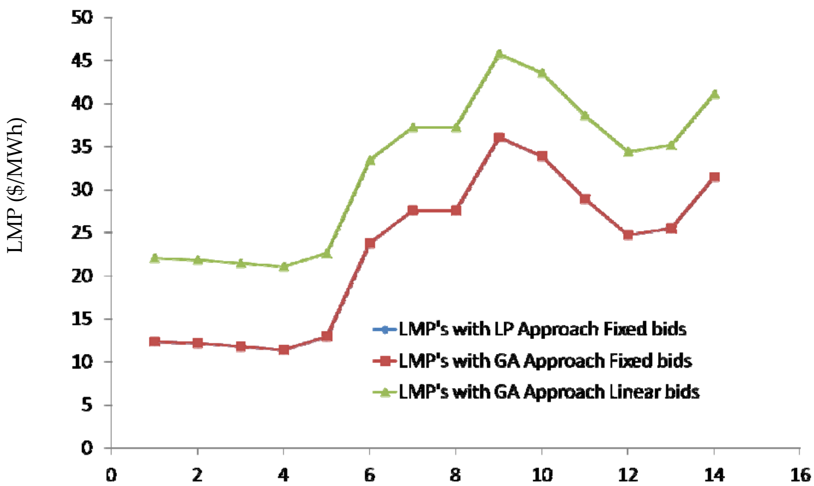

FIG. 4 LMP'S COMPARISON FOR WITHOUT LOSS CASE OF IEEE 14 BUS SYSTEM

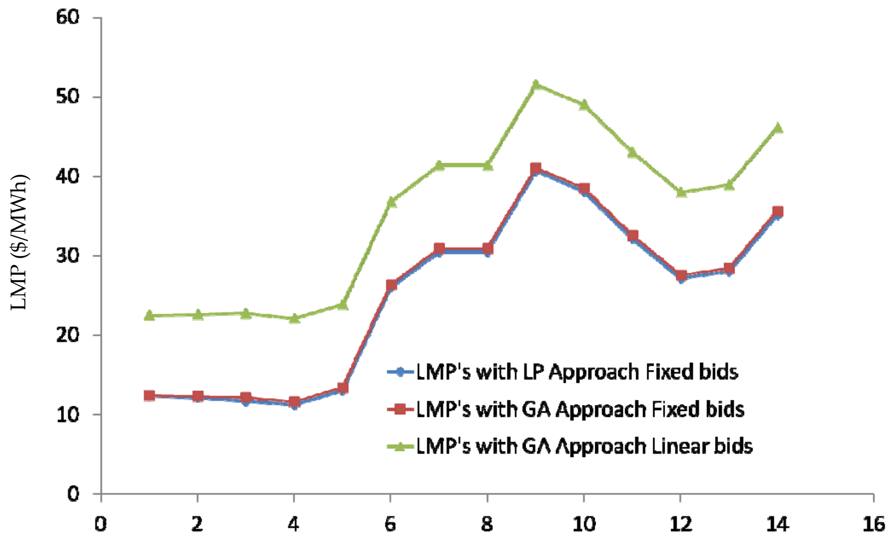

FIG. 5 LMP'S COMPARISON FOR WITH LOSS CASE OF IEEE 14 BUS SYSTEM

75 bus Indian Power System

Similar observations as in the case of 14 bus system are made when the developed algorithm is tested on 75 bus Indian Power System. For base case loading of this system 9th line connecting 4-28 buses is congested in both LP approach and GA approach for both with and without loss cases. The corresponding generations are listed in Table 5. The LMPs at all buses are also calculated for this system.

TABLE 5 ACTIVE POWER GENERATIONS OF GENERATORS FOR WITH AND WITHOUT LOSSES OF 75 BUS INDIAN POWER SYSTEM

Generator bus No.	Power Generations in MW without loss			Power Generations in MW with loss		
	LP approach Fixed bids	GA approach Fixed bids	GA approach Linear bids	LP approach Fixed bids	GA approach Fixed bids	GA approach Linear bids
1 (slack bus)	684.2	730.05	730.05	795.367	793.64	793.64
2	360	282.52	282.52	360	282.52	282.52
3	280	279.93	279.93	280	279.93	279.93
4	185	189.87	189.87	185	189.87	189.87
5	25	25.0	25.0	25	25.0	25.0
6	220	219.95	219.95	220	219.95	219.95
7	160	159.96	159.96	160	159.96	159.96
8	180	179.96	179.96	180	179.96	179.96
9	505.92	201.59	201.59	525	201.59	201.59
10	180	179.96	179.96	180	179.96	179.96
11	209	208.95	208.95	209	208.95	208.95
12	775	1106.8	1106.8	775	1106.8	1106.8
13	1000	999.76	999.76	1000	999.76	999.76
14	250	249.94	249.94	250	249.94	249.94
15	554	553.87	553.87	554	553.87	553.87
Loss (MW)				130.247	63.59	63.59
Fuel cost ($/hr)	56097.0356	55981.2	48528.21	57347.664	56696.62	49237.91

Fig. 6 shows the comparison of fuel costs for 75 bus Indian power system. From Fig. 6 it is observed that optimum fuel cost obtained considering linear bids for generators.

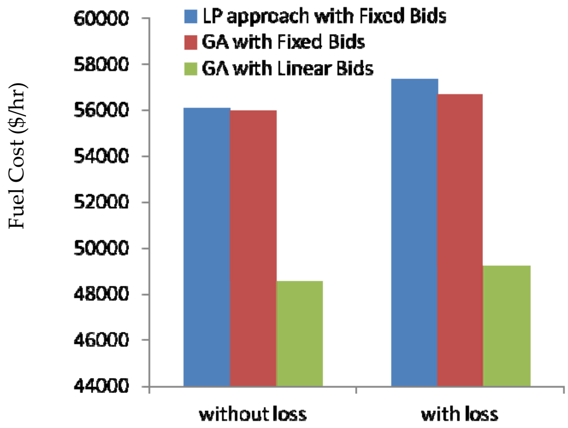

FIG. 6 FUEL COST COMPARISON GRAPH FOR WITHOUT AND WITH LOSSES OF 75 BUS INDIAN POWER SYSTEM

New England 39 bus Test System

For this system also congestion occurred for base case loading only. The generation dispatch for New England 39 bus system is presented in Table 6. For both with and without loss cases of LP approach, lines 37 and 39 are congested. Where as in GA approach line 37 is only congested for both fixed bids and linear bids in the cases with and without loss. Fig. 7 shows the comparison of fuel costs for 39 bus system for all the studied cases. In this system also GA approach with linear bids gives better optimal values of fuel cost. LMP's also are calculated at all buses. The graphs in Figs. 8 and 9 shows the variation of LMP's in the cases with and without loss for all the attempted methods.

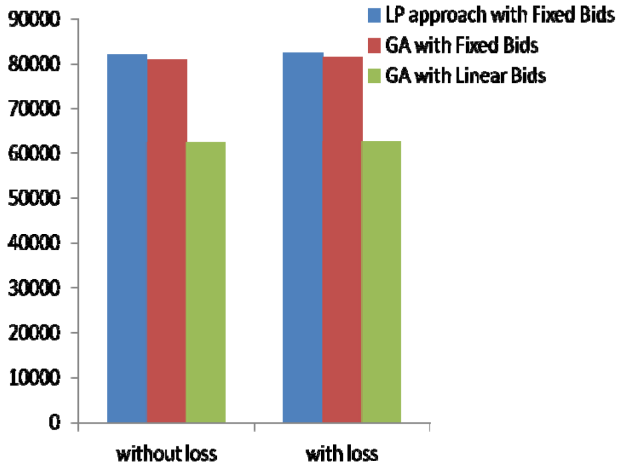

FIG. 7 FUEL COST COMPARISON GRAPH FOR WITHOUT AND WITH LOSSES OF NEW ENGLAND 39 BUS TEST SYSTEM

TABLE 6 ACTIVE POWER GENERATIONS OF GENERATORS FOR WITH AND WITHOUT LOSSES OF NEW ENGLAND 39 BUS TEST SYSTEM

Generator bus No.	Power Generations in MW without loss			Power Generations in MW with loss		
	LP approach Fixed bids	GA approach		LP approach Fixed bids	GA approach	
		Fixed bids	Linear bids		Fixed bids	Linear bids
30	220	300.48	300.48	220	300.48	300.48
31 (slack bus)	609.2	609.1	609.1	643.3	638.55	638.55
32	750	653.35	653.35	750	653.35	653.35
33	650	654.67	654.67	650	654.67	654.67
34	608	548.78	548.78	608	548.78	548.78
35	605	577.6	577.6	605	577.6	577.6
36	406	382.18	382.18	406	382.18	382.18
37	640	506.97	506.97	640	506.97	506.97
38	777.3	818.64	818.64	777.3	818.64	818.64
39	885	1098.68	1098.68	885	1098.68	1098.68
Loss (MW)				34.14	29.45	29.45
Fuel cost ($/hr)	82080.92	81086.69	62351.02	82461.48	81415.38	62686.57

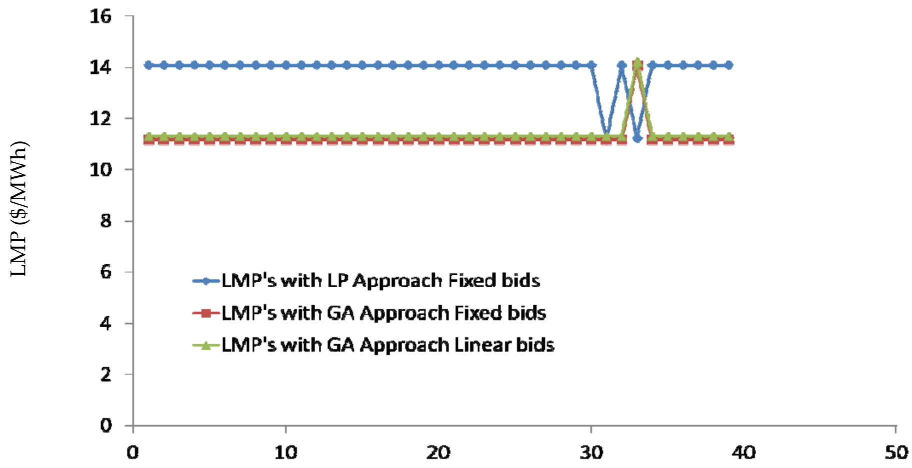

FIG. 8 LMP'S COMPARISON FOR WITHOUT LOSS CASE OF 39 BUS SYSTEM

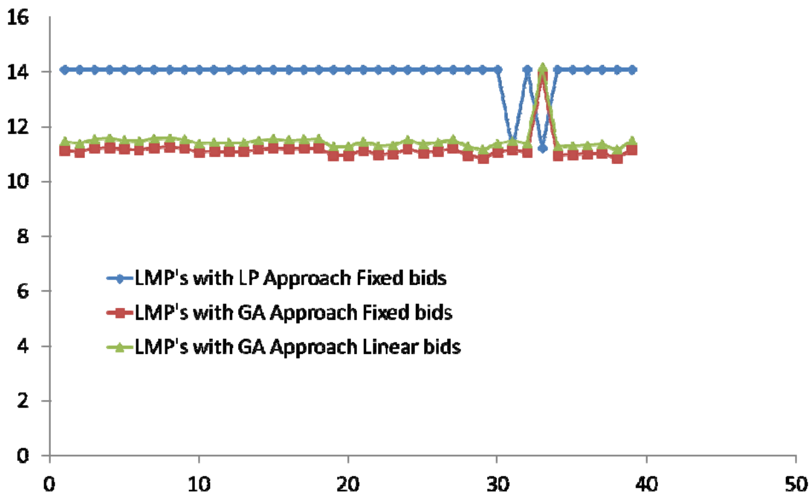

FIG. 9 LMP'S COMPARISON FOR WITH LOSS CASE OF 39 BUS SYSTEM

Conclusions

This paper presented a simple transmission pricing scheme using Genetic Algorithm, considering transmission constraints. The proposed approach is used to evaluate LMP's at all buses in the power system. LMPs with and without losses are calculated with two types of bids i.e., fixed bids and linear bids for the generators. The proposed GA based SCED approach is compared with the LP based DCOPF using Power World Simulator for IEEE 14 bus, 75 bus Indian power system and New England 39 bus test system. It is observed that considerable savings in total fuel cost of generators can be achieved by means of GA based SCED approach with linear bids. LMP's with linear bids are calculated to avoid the non smooth nature of bid curve in fixed bids. In all the studied cases, the GA approach shows a reliable convergence with optimized fuel cost values.

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